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GEOLOGICAL SURVEY OF CANADA
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Physical Exposure to Natural Hazards in Canada

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An Overview of Methods and Findings

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INTRODUCTION

Natural hazard threats occur in areas where buildings, people, and related capital assets are exposed to the physical effects of earth system processes that have a potential to cause damage, injuries, losses, and related socioeconomic disruption. As cities, towns, and villages continue to expand and densify in response to the pressures of urban growth and development, so too do the levels of exposure and susceptibility to natural hazard threat. While our understanding of natural hazard processes has increased significantly over the last few decades, the ability to assess overall physical exposure and levels of susceptibility to the expected negative consequences of future disaster events (i.e., risk) is often limited by access to an equally comprehensive understanding of the built environment and detailed descriptions of who and what are situated in harm's way.

This study is part of a broader initiative led by the Land and Minerals Sector of Natural Resources Canada (LMS/NRCan) to establish an integrated framework of methods, tools, and information to support the assessment of disaster risk at local and regional levels in Canada (Figure 1). It specifically addresses outstanding gaps in our understanding of physical exposure to natural hazards by presenting methods and results of a national model documenting characteristics of the built environment for all settled areas in Canada. To the best of our knowledge, this may be the first attempt to systematically assess the form, function, and internal structure of built-up areas at a sufficient level of detail to support the assessment of natural hazard risk at the community level for all regions in Canada. The assessment includes a more refined spatial mapping of development footprints for all types of urban, rural, and remote settlements, the identification of land use classes describing primary activities that support the day-to-day requirements of residents and businesses at the local level, and the corresponding portfolios of buildings, people, and capital assets that are likely to be present at any given location. Outputs of the CanEM model are used to carry out a preliminary assessment of exposure and susceptibility to significant natural hazard threats in Canada including earthquake ground shaking; inundation of low-lying areas by floods and tsunami; severe winds associated with hurricanes and tornados; wildland urban interface fire (wildfire); and landslides of various types. Full documentation of model development and results for all regions in Canada are described in detail by Journeay et al. (2022, work in progress).

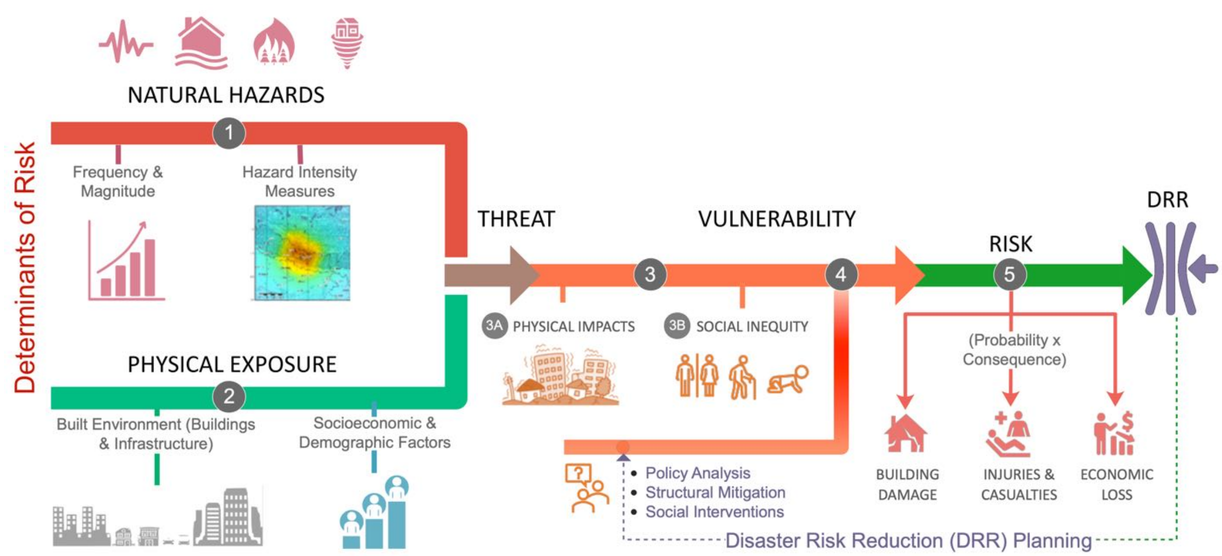


Figure 1: Schematic representation of NRCan's framework for integrated risk assessment. Figure adapted from Freddi et al. (2021).

Model Development

The national physical exposure model (CanEM) is similar in scope and level of detail to other national-level assessments that have been developed to support quantitative risk assessments for the United States, Australia, South America and many parts of Europe (Federal Emergency Management Agency [FEMA], 2011; Nadimpalli et al., 2016; Yepes-Estrada et al., 2017; Crowley et al., 2020). Taxonomies used to describe building portfolios are consistent with those used in the USGS PAGER and Global Earthquake Model Foundation GED4GEM frameworks (Jaiswal et al., 2014; Silva et al., 2018; Silva et al., 2022). Although designed specifically to support the quantitative assessment of earthquake risk at the community level, model schemes are configured to support emerging interoperability standards established as part of the MOVER framework for multi-hazard risk assessment (Murnane et al., 2019) and the translation of these schemes into formal data models established by the INSPIRE directive to support system interoperability (INSPIRE, 2013, 2017). Key steps in the model development process are summarized in Figure 2.

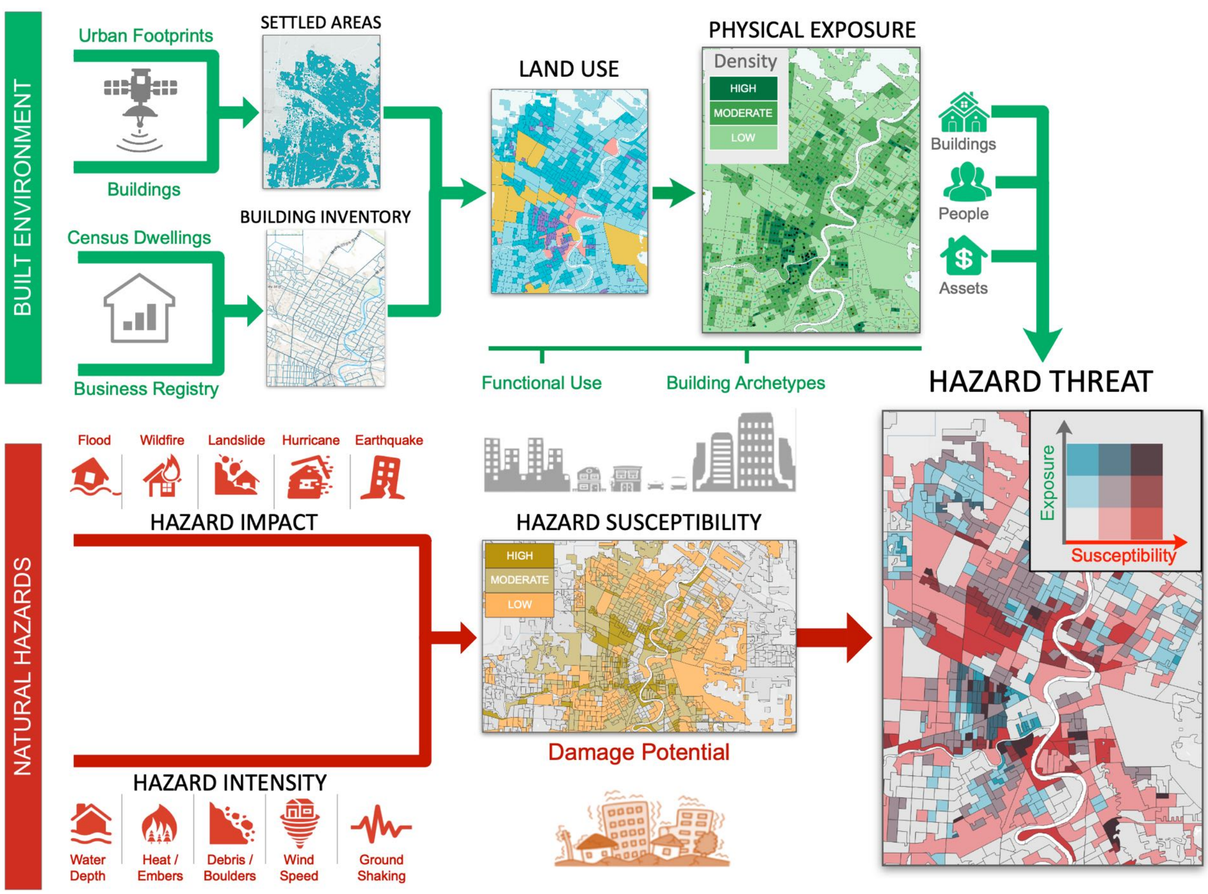


Figure 2: Model structure and general workflow used for assessing exposure and physical threats associated with natural hazards in Canada

Settled Areas

While the overall model development process is comparable to other national-level assessments, additional capabilities have been developed to address patterns of human settlement and the associated characteristics of physical exposure that are unique to large and sparsely settled countries like Canada. The identification of built-up areas is based on (i) available land cover information derived from 30m satellite imagery (Fisette et al., 2006; Natural Resources Canada, 2015), and (ii) vector-based photogrammetric surveys that define the spatial extent of amalgamated neighbourhoods in larger population centres, and the locations of isolated building clusters that occur in rural hinterland and remote settings of the country (Natural Resources Canada, 2017). Each settled area (SA) is identified based on its membership in one of eight broad settlement types (e.g., urban core, suburb, rural community, remote settlement), and characteristics of land tenure that reflect both ownership and land management authority (Statistics Canada, 2016; Natural Resources Canada, 2021). This includes whether lands are managed by local and regional authorities under provincial/territorial jurisdiction, designated as First Nation reserve lands and administered by Tribal Councils and local authorities under federal jurisdiction, or self-governed through negotiated land claims that are specific to the Inuit and other Indigenous Peoples of Canada.

Aggregate Building Inventory

Aggregate building counts are derived from census-based population and housing statistics reported at the dissemination area level (Statistics Canada, 2016) and from available national business registries (Dun & Bradstreet, 2011; Emporis International, 2017). Characteristic building functions are described using standard North American building occupancy classes developed to support implementation of the HAZUS methodology in the United States (Federal Emergency Management Agency [FEMA], 2004). The number and type(s) of residential buildings are estimated by dividing the total number of census dwelling units of a given housing type by the corresponding average number of dwelling units per structure. Non-residential building counts are estimated based on the number of unique business listings that share the same street addresses and/or geographic coordinates. Dominant building functions are inferred from standard North American Industrial Classification System (NAICS) code descriptions. Average floor area and height estimates for each unique occupancy class are based on information collected as part of Canada's national survey of commercial and institutional energy use (Natural Resources Canada, 2014), site-level building inventories compiled from taxation records for the Metro Vancouver region (Journeay et al., 2015), and FEMA P58 building inventory guidelines (Hamburger et al., 2018). This information is used to assess both the number of building occupants that are likely to be present at different times of day, and the costs to replace buildings and contents that may be damaged in the event of an earthquake.

Residential populations are estimated by multiplying the number of people per dwelling during nighttime hours (i.e., permanent occupants) by the average number of dwellings per building in each occupancy class. The numbers of residential and non-residential building occupants during standard workday hours (9am-5pm) and during commuting hours when people are in transit (7am-9am; 5pm-7pm) are estimated as a proportion of the total nighttime population using guidelines established as part of the Hazus methodology (Federal Emergency Management Agency [FEMA], 2011). Non-residential building occupants are estimated by multiplying the average number of employees per 1,000 square feet during daytime hours (9am-5pm) by the total finished building area for each occupancy class. The number of building occupants at other times of day are calculated using guidelines established as part of the FEMA P58 methodology (Hamburger et al., 2018). As population estimates for non-residential buildings are highly sensitive to local variations in finished floor area used in the calculations, a final adjustment is made to ensure that the number of full-time residents within a given census subdivision are within a few percent of values reported by the national census.

Asset valuation is based on the estimated costs to construct, repair, or replace the structural envelope of a building (foundation, load-bearing walls, roof), non-structural components of the building (ceilings, mechanical equipment, fixtures) and ordinary building contents including personal belongings or commercial merchandise. Asset valuation is based on industry standard construction costs (CAN$/ft2) for reference building archetypes in eleven census metropolitan areas across Canada (Moselle, 2017; Turner & Townsend, 2017; Altus Group, 2018, 2020). Regional variations are adjusted based on statistical profiles compiled as part of the Canadian Consumer Price Index (Chiru et al., 2015). Replacement costs are estimated by multiplying regional unit costs per square foot by the corresponding finished floor area for each building in the national inventory. The determination of construction quality is based on mean building age as determined from census data and alignment with safety design guidelines of the national building code that are assumed to have been in place at the time of construction.

Land Use and Building Archetypes

Functional profiles of land use are based on a neighbourhood-level classification that identifies six dominant archetypes for all developed areas in the national settled area fabric based on characteristics of density and the mix of residential and non-residential building occupancies at a given location. These include three urban residential neighbourhoods of varying density, mixed-use commercial/industrial lands with minor residential components, and low-density rural residential lands. Analytic methods used to interpret land use classes are comparable to those developed in the fields of landscape architecture and urban planning to model patterns of energy demand and corresponding emission profiles at the community level (Song et al., 2007; Clifton et al., 2008; Salter et al., 2020).

In addition to representing broad system interactions based on characteristics of form and function, land use classes are also effective in establishing context-specific mapping schemes that are used to assess the relative proportions of building types likely to be present at a given location based on statistical correlations between specific occupancy class and corresponding construction types. Site-level inventories are used to establish reference mapping schemes for specific regions of the country where these relationships have been observed and measured (Onur, 2002; Zaleski, 2014; Journeay et al., 2015; Bebamzadeh et al., 2018; Ploeger et al., 2018). Correlations between construction type and building occupancy that are specific to each of the land use classes represented in these source datasets are used to develop frequency distributions that guide the allocation of building archetypes within each settled area in the national fabric. These reference mapping schemes are then adjusted for use in other regions of the country based on more general relationships between construction type and occupancy class derived from building construction data compiled for each province and territory in Canada (Statistics Canada, 1990), and from equivalent regional mapping schemes developed to support implementation of FEMA's HAZUS loss estimation methodology in neighbouring regions of the U.S. (FEMA; 2004; 2011).

Building archetypes are based on the HAZUS taxonomy, which includes 33 residential and non-residential occupancy classes and 38 engineering-based descriptions of building types and corresponding load-bearing systems that reflect overall construction quality and degrees of alignment with seismic safety design guidelines established by the national building code. The full taxonomy includes ~1,585 distinct types of building structures representing 496 unique combinations of occupancy class and construction type across 4 levels of seismic design. A random sampling process is used to allocate building archetypes for each settled area polygon based on the total number of specific building occupancies at a given location and corresponding mapping schemes that establish the proportional distribution of construction types that are associated with each land use class in different regions of the country. These higher level designations are then assigned to one of four seismic design levels based on exposure to known seismic hazards, the estimated year of construction, and alignment with building safety design provisions of the national building code that are assumed to have been enforced at the time of construction.

Susceptibility to Natural Hazard Threats

Our analysis of multi-hazard threat is based on open-source probabilistic hazard models that predict spatial patterns and intensity levels for earthquake, tsunami, flood, and hurricane events that are likely to occur over a ~ 500-year period (Annual Exceedance Probability = 0.2%), and scenario-based forecast models that predict wildfire, and landslide hazards based on seasonal weather and land cover conditions. The assessment considers both the overall exposure to each of these hazard threats and expected degrees of severity based on empirical damage scales that relate the physical susceptibility of people and building assets to measured hazard intensity levels at a given location. Analytic methods and results are consistent with other multi-hazard assessment frameworks that have been developed for assessing patterns of hazard threat to inform planning and policy development at regional and local scales. These include: the Americas Indexing Program for the Caribbean and South American countries (Cardona et al., 2005); the Integrated Risk Assessment of Multi-Hazards Framework for the European Union (Greiving, 2006; Greiving, 2007); the global Index for Risk Management (INFORM; De

Groeve et al., 2015; Marin-Ferrer et al., 2017); and the National Risk Index (NRI) for the United States (Federal Emergency Management Agency [FEMA], 2020).

KEY FINDINGS AND INSIGHTS

Results of our assessment provide important new insights on patterns of development, physical characteristics of the built environment and the effects of ongoing urbanization on escalating disaster risk trends for communities that are situated in harm's way. National-level profiles of physical exposure and hazard susceptibility are accompanied by open-source datasets that provide a capacity to support local and/or regional assessments of disaster risk, community planning and emergency management activities for all areas in Canada. Collectively, these outputs contribute to broader policy objectives established through the International Sustainable Development Goals (SDG 2015-2030; Un General Assembly, 2015) and the Sendai Framework for Disaster Risk Reduction (SFDRR 2015-2030; United Nations Office for Disaster Reduction [UNDRR], 2015), of which Canada is a contributing member. These include increased scientific capacities to model the combined physical and social dimensions of natural hazard threats; the effective translation of this knowledge into a base of evidence that promotes a more holistic understanding of disaster risk at all levels of government; and the implementation of actionable strategies that are effective in reducing both intrinsic vulnerabilities and strengthening the capacity of communities to withstand and recover from future disaster events.

Developed Areas of Canada

The settled area fabric of Canada encompasses ~128,400 square kilometres of developed land, which represents ~ 1% of the total land surface area in Canada. Rural and remote settlements make up the largest proportion of developed areas (~62% of total) with metropolitan regions along Canada's southern border making up the balance. Although representing a smaller geographic area overall, densely settled metropolitan regions account for more than 83% of the total national population (29.2M out of 35.1 million people) with most Canadians living in one of ~ 50 major urban centres of greater than 100,000 people. As it turns out, many of these larger metropolitan regions are situated in areas exposed to significant levels of natural hazard threat.

Integration of these more detailed development footprints with available national census data and non-residential building inventories provides a means of assessing not only *who* and *what* will be most affected by future disaster events but also the relative scale of impact for different locations within a community or region. Identifying characteristic patterns of land use within these developed areas and the corresponding portfolios of building types that are likely to be present at a given location provide additional information on how disaster impacts are likely to be concentrated within a community, and the range of socioeconomic activities that are likely to be disrupted by the immediate physical impacts to buildings, loss of shelter and disruption of essential business services in the days, weeks and months following a disaster event. Patterns of human settlement and land use identified as part of the CanEM model also establish an important baseline for assessing the implications of ongoing growth and development for those communities that are exposed to significant natural hazard threat in Canada.

Model results contribute to ongoing global efforts to measure the effects of urbanization over time and to monitor its influence on evolving patterns of disaster risk at national and sub-national scales (Statistics Canada, 2015; European Commission- Joint Research Centre, 2020). Collectively, these studies show an increase in the land area being used for development in Canada and a re-distribution of people into more densely populated urban centres. Over a forty-year period (1975-2015), it is estimated that the share of people living in rural and remote settings has decreased by 5% and 6.5%, respectively. Similar reductions are documented in lower density suburban neighbourhoods surrounding major metropolitan regions where the number of people relative to the total national population has decreased by 7.1%. The relative proportion of people living in high-density urban centres over this same period has increased from ~47% of the total national population in 1975 to ~65% in 2015. These trends in urbanization and the re-distribution of people into areas that are exposed to significant natural hazard threat are projected to continue over the next forty-year period (Chagnon et al., 2019). The pressures of ongoing growth and development will affect patterns of densification and land use that are likely to exacerbate escalating trends in disaster risk for many communities across Canada, including Indigenous communities living on Aboriginal lands that are already experiencing levels of housing stress and more limited access to critical infrastructure services.

A Model of the Built Environment

As summarized in Figure 3, there are an estimated ~9.7 million structures in Canada representing an overall capital asset value of ~CAN$8.24 trillion. Collectively these buildings provide housing and business services to ~35.15 million people in a wide range of geographic settings and settlement types. More than three-quarters of all buildings (~7.3 million structures) and related capital investments (CAN$6.83 trillion) are concentrated in higher-density metropolitan regions that collectively represent ~35% of the total developed area in Canada (44,585 km2). These physical assets are distributed primarily in single and multi-family urban residential, mixed-use commercial/industrial neighbourhoods. In contrast, rural hinterland areas represent ~62% of all developed lands in Canada (78,780 km2) and yet account for only ~23% of the total building inventory (2.24 million structures) and ~16% of the total population and related capital investments (5.62 million people; CAN$1.34 trillion). Remote settlements encompass only ~3.5% of all developed areas (4,470 km2) and account for ~1% of the total building inventory (~103,450 structures) and less than 1% of the total population and related capital investments (~295,200 people; CAN$74.3 billion).

The highest concentration of physical assets is in the central Canadian Shield and adjacent St. Lowland regions of Ontario and Quebec, followed by the combined developed areas of the Interior Prairie provinces of Alberta, Saskatchewan, and Manitoba (see Figure 3). The western Cordilleran region of British Columbia ranks third overall and is characterized by a high proportion of buildings, people, and capital assets relative to the area of developed land while the reverse is true for the Eastern Maritime provinces of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador. More remote towns, villages, hamlets, and dispersed settlements in northern regions of the Yukon, Nunavut, and the Northwest Territories represent ~3% of all developed lands by area and less than 1% of the total inventory of buildings, people, and capital assets. Approximately 2% of all people and building assets in these regions are situated on Aboriginal lands. This includes an estimated population of 636,700 people living on First Nations reserves, Métis settlements or Inuit-owned lands, and a building inventory of 193,060 structures with an overall replacement value of ~CAN$151.3 billion.

Knowing the spatial distribution and relative concentrations of building archetypes within a given community or region provides insights on which places are likely to sustain higher levels of damage based on the performance characteristics of specific construction types to different types of hazard threats. For example, we know from forensic studies of historic disaster events that older unreinforced concrete and masonry buildings do not generally perform well when subjected to significant body forces associated with severe earthquake ground shaking and the direct physical impacts associated with various types of landslides. Similarly, older wood frame buildings that predate modern safety design guidelines in Canada's National Building Code are generally more vulnerable to the physical impacts of severe wind and wildfire. Engineering-based information on building materials, load-bearing systems and relative age of construction also provide a foundation for the development of physical vulnerability models that are used in quantitative risk assessments to measure anticipated levels structural damage and related patterns of injury, economic loss, and social disruption for future disaster events. Building fragility and physical vulnerability functions derived from the CanEM model are currently being used to support a national assessment of seismic risk in Canada (Silva et al., 2020; Hobbs et al., 2022; Journeay et al., work in progress, 2022), and have the potential to be adapted for use in evaluating profiles of disaster risk for other hazards of concern including floods, hurricanes, wildfire and landslides.

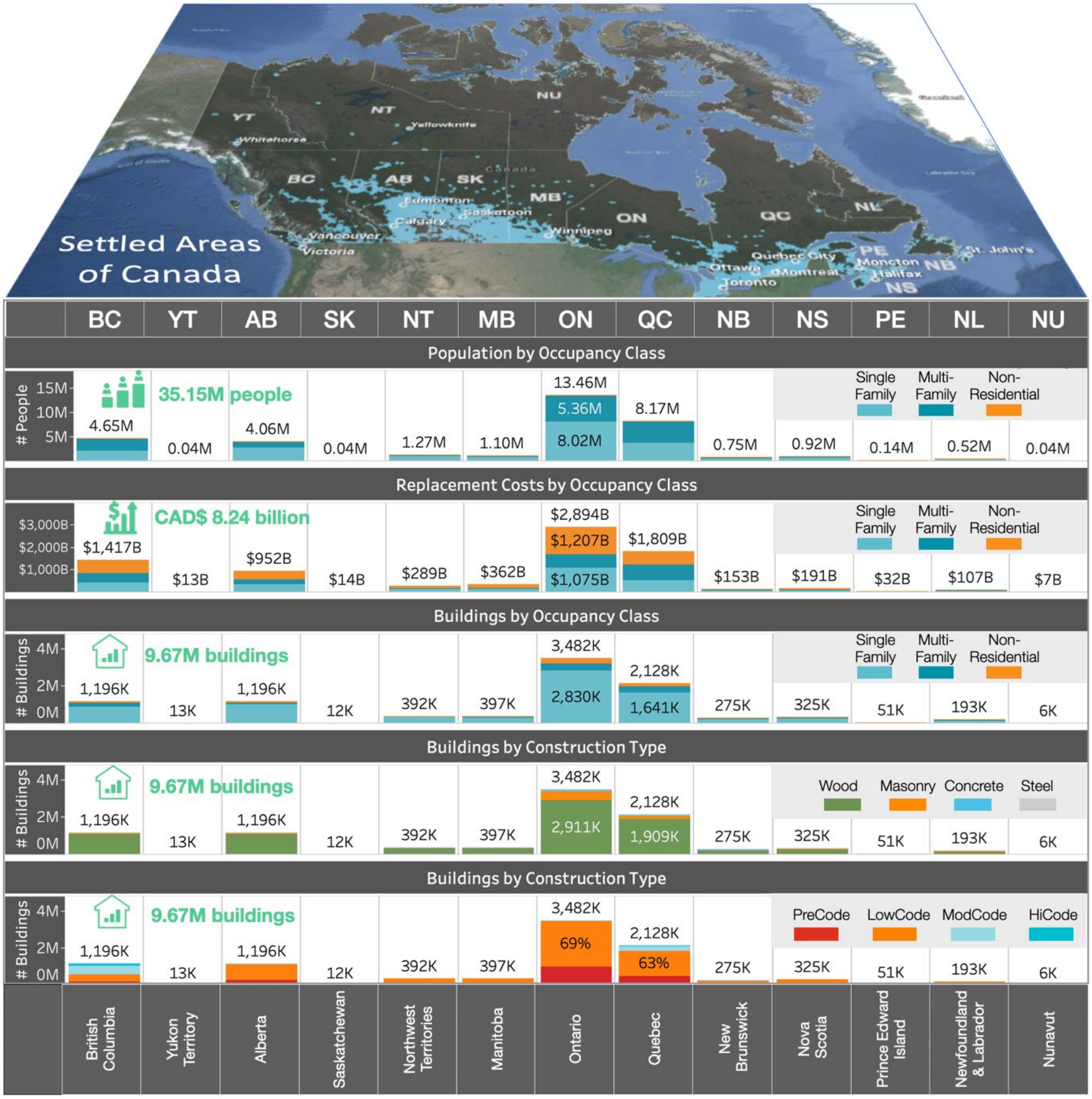


Figure 3: Regional distributions of built-up areas, people and building assets for provinces and territories of Canada.

Who and What Are in Harm's Way?

Canada is exposed to a wide range of natural hazards due its geographic size and physiographic diversity. These include flood, wildfire, landslide, and tropical cyclone events that occur on a more regular basis throughout the country, and rare but potentially catastrophic earthquakes, tsunamis, and volcanic eruptions that are known to affect specific geologic regions. Each of these hazards has a characteristic profile of likelihood, magnitude, and potential for negative consequences that varies from place to place as a function of geographic setting and physical exposure.

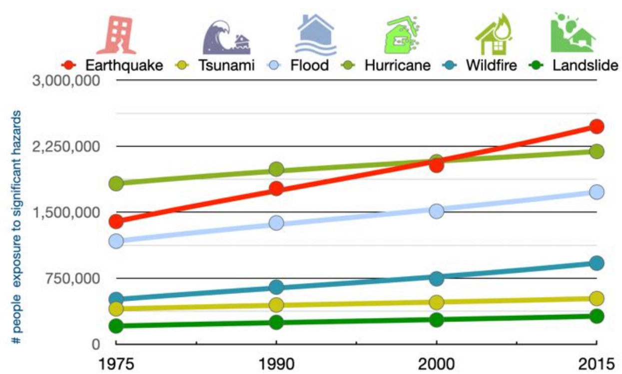
Preliminary results of this study provide a baseline for assessing who and what are situated in areas exposed to natural hazard processes that may pose a threat to public safety, physical assets, and/or socioeconomic well-being (see Table 1). In order of overall physical threat, earthquakes and hurricanes are shown to directly affect the largest number of people, buildings, and financial assets, followed by riverine floods, wildfire, landslides, and tsunami. Although a smaller number of physical assets are susceptible to hazard intensities capable of causing structural damage, the level of threat is significant with levels of disaster risk that would likely result in fatalities, injuries, household displacement and related socioeconomic losses.

Table 1: Preliminary hazard threat profiles for earthquakes, tsunamis, floods, wildfire, and landslides in Canada based on the CanEM physical exposure model and publicly available hazard assessment information.

Hazard Types		Earthquake		Tsunami		Hurricane		Flood		Wildfire		Landslide	
Exposed Assets		>3.9%g	>18%g	>25%	>50%	>119 km/h	> 178 km/h	>30 cm	> 1m	>500 kW/ m2	> 2,000 kW/m2	LndSus >2	LndSus > 3
Buildings	9,665,398	4,802,830	570,925	320,652	142,793	3,259,088	778,321	2,178,395	448,797	921,540	353,989	985,612	189,104
	% of Total	50%	5.9%	3.3%	1.5%	33.7%	8.1%	22.5%	4.6%	9.5%	3.7%	10.2%	2.0%
People	35,151,729	19,772,174	2,528,425	1,095,368	523,520	11,624,692	2,163,973	7,209,683	1,341,384	2,821,250	1,079,443	2,836,601	509,853
	% of Total	56%	7.2%	3.1%	1.5%	33.1%	6.2%	20.5%	3.8%	8.0%	3.1%	8.1%	1.5%
Assets (m $CAD)	$8,240,184	4,530,872	751,715	327,336	164,525	2,552,180	446,545	1,825,273	341,416	664,051	253,431	760,328	145,455
	% of Total	55%	9.1%	4.0%	2.0%	31.0%	5.4%	22.2%	4.1%	8.1%	3.1%	9.2%	1.8%

Table 2: Temporal variations in physical exposure to natural hazard threats in Canada over a forty-year period (1975 to 2015).

Epoch	1975	1990	2000	2015	40-year Growth Rate
Total Population	23,123,727	27,645,165	30,685,096	35,922,368	55%
Earthquake	1,394,203	1,769,376	2,031,354	2,474,165	77%
Tsunami	401,174	445,678	473,619	518,937	29%
Flood	1,170,504	1,378,230	1,510,409	1,728,920	48%
Hurricane	1,824,691	1,989,578	2,073,221	2,190,451	20%
Wildfire	508,197	648,299	742,601	921,029	81%
Landslide	206,233	248,306	275,521	318,294	54%



These results help make evident how characteristics of the built environment may be controlling profiles of disaster risk for many communities across Canada and contribute more generally to global assessments of multi-hazard threat that measure the effects of urbanization over time. Models of global exposure to natural hazards document changes in the numbers of people exposed to various natural hazards over a 40-year period (1975-2015) and a at a spatial resolution of ~250 metres (Pesaresi et al., 2018). Population estimates used in these global models are derived from national census information and are within a few percent of 2016 census values.

A comparison of historical trends with more detailed assessments of the built environment carried out as part of this study provide insights on how patterns of hazard threat have changed in Canada at local and regional scales (see Table 2). For example, physical threats associated with flood and landslide hazards are shown to have increased over a forty-year period at rates that are comparable to overall trends in population growth (48-54%). Physical threats associated with hurricane and tsunami have increased at much lower rates (20-29%) while those associated with earthquakes and wildfire have increased by 77% and 81% (respectively) over this same period.

Lower rates of growth for hurricane and tsunami threats may be related to the relocation of people from rural and remote communities of the eastern Maritimes and western Cordilleran regions to other parts of Canada (Chagnon et al., 2019). More rapid rates of growth for earthquakes and wildfire threats are attributed to a corresponding increase in the numbers of people moving into densely populated urban centres that are situated in areas exposed to more severe ground shaking hazards in British Columbia and Quebec, and the more general expansion of development into both urban and rural areas exposed to wildland interface fire hazards. It is anticipated that these trends will likely continue but at slower rates of growth over the next forty years.

THE PATH FORWARD

While model results described in this report establish an important baseline for evaluating the relationships between ongoing development and escalating disaster risk trends, we recognize that additional work will be needed to establish the necessary base of evidence for both disaster resilience planning and policy development at the community level. Our intent is to work in partnership with other public, private, and academic sector organizations to address both current limitations and update the national exposure model as new and more refined information becomes available. To this end, we are releasing this initial version of the national model as an open-source geospatial database to support collaboration with public, private, and academic sector organizations who may share an interest in co-developing future iterations of the model (OpenDRR Platform: https://opendrr.github.io/en/index.html).

The current version of the CanEM model is best suited for use at local and regional scales (e.g., census dissemination area) with overall levels of accuracy expected to improve at higher levels of aggregation. For example, the spatial distributions and classification of buildings by occupancy class, construction type and/or age are likely to consistent with site-level inventories at the scale of a community or region, even though there may be uncertainty in the specific mix of building types at a given location. As a result, hazard threat assessments aggregated at the level of census subdivisions or higher would be appropriate for use in the context of emergency response and recovery planning where there is a need to understand the spatial extent and distribution of expected physical impacts for a given region – and the overall numbers of people, buildings, and related financial assets that are likely to be affected at the community level.

Model results aggregated at the level of individual settled areas are appropriate for use in understanding variable patterns of physical threat within a given community but should only be used when assessing natural hazard processes that affect large geographic regions in which there are relatively small intensity variations from one location to another. These include earthquake, tsunami, and volcanic hazards that are controlled by crustal scale geophysical processes, and hurricane and wildfire hazards that are controlled by global hydrometeorological systems. However, for intensive hazards including riverine floods and landslides, we recommend the use of both site-level building inventories and the most detailed hazard models available for assessing both overall exposure and levels of susceptibility to specific hazard threats within a particular community. Building portfolios at all scales of aggregation can be filtered by land use class, building occupancy, and/or construction type to help illuminate underlying characteristics of the built environment that may be contributing to regional patterns of disaster risk.

Opportunities for Future Work

While there is not yet a capacity to inform risk management decisions at the property level, existing models do help provide important insights on the challenges that lie ahead for many communities across Canada. It is our hope that results of this study will provide a useful base of evidence to inform hazard and risk assessments and establish the necessary foundation for ongoing collaboration and model refinements that will be needed to support disaster resilience planning and policy development at a community level.

Specific opportunities to improve the national exposure model and national hazard threat assessments include:

Physical Exposure Model

- Development of site-level inventories to better constrain the predictive capabilities of aggregate building portfolio models. This includes the compilation and synthesis of (i) non-proprietary survey information derived from provincial tax assessment records and municipal business listings that provide important details on floor area, number of stories, building occupancy, year of construction/significant renovation, and fixed capital replacement costs, and (ii) critical infrastructure facilities and associated linear distribution networks for essential water, power, transportation, and communication services. This information is urgently needed to better understand the resistance of critical infrastructure systems to the physical impacts of various natural hazards, and the potential for cascading failures within interdependent lifeline systems that can undermine recovery efforts following a disaster event (i.e., systemic risk).
- Predictive modeling of future growth and development scenarios to assess how the distributions of buildings and people are likely to change over time. When coupled with physical risk models, these development scenarios offer critical insights into factors that are driving escalating disaster risk trends and assist in the evaluation of adaptation/mitigation strategies that might be considered to reduce physical vulnerability and associated levels of risk at the community level. The analytic methods needed to address these challenging questions have been developed and validated in other regions (Calderón et al., 2021), and could be implemented here in Canada based on available growth projections that are routinely developed by local and regional authorities to support growth management, spatial planning and land use decision making.
- Use of machine learning techniques to improve land use classifications and the prediction of building archetypes based on available site-level inventories. This is particularly relevant for improving existing characterizations of building portfolios for the Interior Prairie and Maritime Provinces and for northern boreal forest and arctic regions of the Yukon, Northwest Territories and Nunavut where building practices have been adapted to accommodate more severe climate conditions.

Natural Hazard Susceptibility

- Refinement of national-level hazard models to better reflect the potential impacts of localized hazard processes such as flood inundation (riverine, pluvial, coastal storm surge, and tsunami), hurricane winds, wildfire ignition, and landslides of various types. Many of these models exist and are currently used in private/academic sectors for catastrophic risk modeling carried out on behalf of the insurance industry, municipalities, and enterprise-level owners and operators of critical infrastructure. Strategic public-private-academic partnerships offer the potential to develop open-source ensemble models that leverage the best available science while enhancing opportunities for both new research and the expansion of professional services.
- Refinements of existing building taxonomies and supporting information architectures to better align with emerging international standards (Murnane et al., 2019). This includes both the addition of key building attributes, including first floor elevation, foundation type, and presence of basements, that are required to analyze flood risk, and characteristics of roof construction that are required to analyze physical impacts caused by severe wind and wildfire hazards.
- Co-development of engineering-based fragility and vulnerability functions that better reflect the specific performance characteristics of buildings constructed in Canada across a range of hazard types. While this information exists for many hazards and is routinely used in the private sector for assessing property-level risk, there are opportunities to generalize the outputs of these empirical models for use in assessing risks at higher levels of aggregation using representative building archetypes.

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